NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1140

Multikilowatt Solar Arrays

D. W. Ritchie

J. D. Sandstrom

Approved by:

P. Goldsmith

P. Goldsmith, *Manager*
Spacecraft Power Section

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

July 15, 1967

TECHNICAL REPORT 32-1140

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

Contents

Table

Figures

Abstract

The ever-changing field of photovoltaics has led to significant improvements which enhance its consideration for multikilowatt systems. Specifically, large-area, lightweight structural developments along with new silicon technology indicate the feasibility of multikilowatt solar arrays with specific power densities approaching 40 lb/kw. In addition, thin film technology, namely, CdS-type photovoltaic devices, promises even greater potential in the future. Current development efforts being conducted by JPL and industry are presented.

Multikilowatt Solar Arrays

I. Introduction

The first decade of space exploration is nearly completed, and the silicon solar cell continues its role as the dominant power source for long term spacecraft operation. To date, photovoltaic arrays have been used in spacecraft power systems where system demands have been less than 1 kw. The photovoltaic array has demonstrated its capabilities in near-Earth, lunar, and interplanetary environments. Each of these environments imposes special consideration on the design of the photovoltaic array system.

The photovoltaic solar array power system has been identified as an interim type system to be replaced by more sophisticated and higher power capability type devices. Presently there are such spacecraft solar array systems as *Orbiting Astronomical Observatory*, *Mariner IV*, and several United States Air Force vehicles that exhibit power capability between 600 and 1,000 w in a near-Earth space environment. Each year technology advances have been realized in launch vehicle payload capability, and subsequently spacecraft systems have increased in size and power demands. Recent studies indicate that future spacecraft systems may be able to consider photovoltaic arrays up to 50 kw in size.

There are several potential spacecraft systems under analysis which could utilize multikilowatt solar array systems. These include manned applications, communications satellites, and interplanetary ion propulsion thrust systems for unmanned space exploration. Each of these systems imposes several design restraints on the solar array. The most severe of these is the ion propulsion type vehicle where power demands are at extremely high levels and total solar array weight is restricted to a maximum of 50 lb/kw, requiring a significant advance in solar array technology.

The present capabilities of photovoltaics are probably best represented by the *Mariner IV* solar array system. The particular solar cell used on *Mariner IV* exhibited an air mass zero (AM0) power density at a temperature of 55°C of 9.7 w/ft^2. The *Mariner IV* solar array system deployed a total of 70 ft^2 and exhibited a total system weight of 100 lb/kw.

The expansion of technology through developments in photovoltaics, structure techniques, materials, and deployment systems are major contributing factors leading to the advancement of multikilowatt, lightweight solar array systems. This report deals in the areas of solar cell developments, including: thin silicon, dendritic and cadmium sulfide-type cells, as well as the possible improvements in large area, lightweight arrays approaching 50 lb/kw or less.

II. Status of Silicon Technology

The workhorse N/P silicon solar cell of today has evolved from user demands and has been optimized mainly for near-Earth environments. The increasing interest of the photovoltaic system for high power, lightweight, and deep space applications entails further optimization of the silicon solar cell. Recent studies indicate that photovoltaics may be used in extreme environments such as Mercury and Jupiter. These requirements impose operating ranges to the photovoltaic system at intensities and temperatures not normally encountered by photovoltaics. The operating characteristics of cells at these environments are presently being investigated. Present trends in photovoltaic usage are toward weight optimization and high efficiency, as well as establishing operating limits.

The present status of the solar cell is well defined by Cherry and Zoutendyk (Ref. 1), although slight improvements have since been realized in weight optimization of the silicon solar cell. The N/P silicon solar cell is the only photovoltaic device now in large-scale production in the United States. The N/P solar cell is available in many configurations and is processed by three main techniques: single crystal P-doped silicon blanks with phosphorus diffusion, single crystal P-doped silicon blanks with phosphorus diffusing using ion implantation, and polycrystalline P-doped silicon blanks using dendritic growth and phosphorus diffusion. Of these, the first method is the one employed today in large production. The other methods are in the pilot line production stage. The AM0 efficiency of the N/P silicon solar cells is in the range of 10 to 11% at 28°C.

One of the more recent developments in the silicon solar cell relates to the power density of the device itself. Wolf and Ralph (Ref. 2) performed experimental and theoretical investigations of the performance of solar cell short circuit current (I_{sc}) as a function of silicon thickness. The results of these investigations showed that the I_{sc} and the corresponding maximum power decreased as a function of cell thickness (Fig. 1). However, increased specific power can be gained with the thinner, reduced efficiency, silicon solar cells because of the more significant overall weight reduction. The sunlight efficiency and power density of the silicon solar cell is plotted as a function of cell thickness in Fig. 2. It is obvious that the thinner cells show dramatic weight savings when the cell alone is regarded.

In considering the usefulness of the thinner silicon solar cells, it is important that the temperature and intensity characteristics exhibit parameters similar to the more common 0.018-in. thickness solar cell. The characteristics of 0.008-in. thickness solar cells have been taken at intensities from 30 to 180 mw/cm^2 and temperatures from -10 to 60°C. As indicated in Figs. 3 and 4, the characteristics of the 0.008-in. thickness (N/P) cell as compared to the 0.018-in. thickness (P/N) cell show that the parameters of the thin silicon solar cells are comparable to the thicker cells and could be utilized as a power source with confidence.

To enhance usage of silicon solar cells to satisfy multikilowatt requirements, attractive cell efficiencies and power densities (w/lb) must be obtained. Photovoltaic developments for the past two years have been geared to these objectives. The present state of the art of solar arrays is about 10 w/lb and 10 w/ft^2. The weight breakdown of the sun-oriented type solar array consists of about 40% cells, cover glasses and interconnections, and about 60% structures and deployment mechanisms. The solar cell stack (Fig. 5), typical of sun-oriented type arrays, exhibits the state of the art as it was in 1965. The potential of future type cell stacks using silicon technology advancements and integral filter systems is presented in Table 1.

III. Photovoltaic Developments

The use of an integral cover slip has been under development for several years and is recognized as a significant advancement in solar array processing and weight reduction. There are various techniques under development and evaluation to accomplish the integral coating. Present techniques are available to apply coatings in the 0.001-in. to 0.003-in. thickness range with little power loss from the cell. Figure 6 represents a typical *I-V* curve of an 0.008-in.-thick solar cell before and after application of an 0.001-in.-thick SiO_2 integral coating. Present indications of the economy of such a system reflect considerable saving in the integral coating technique. The coatings have not been *space proven*; however, they do exhibit a promising potential for future usage.

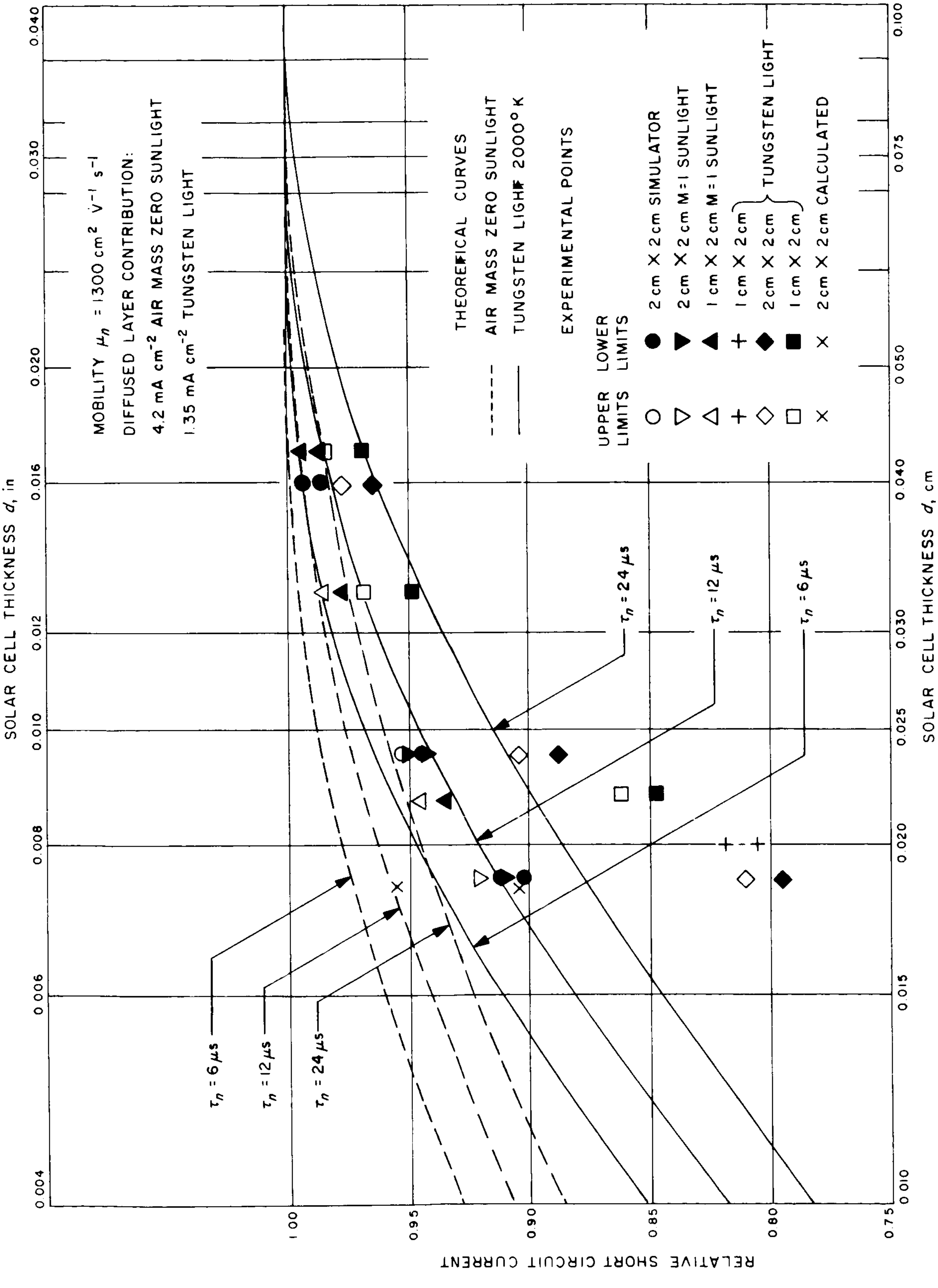

Fig. 1. Effect of I_{sc} as a function of cell thickness

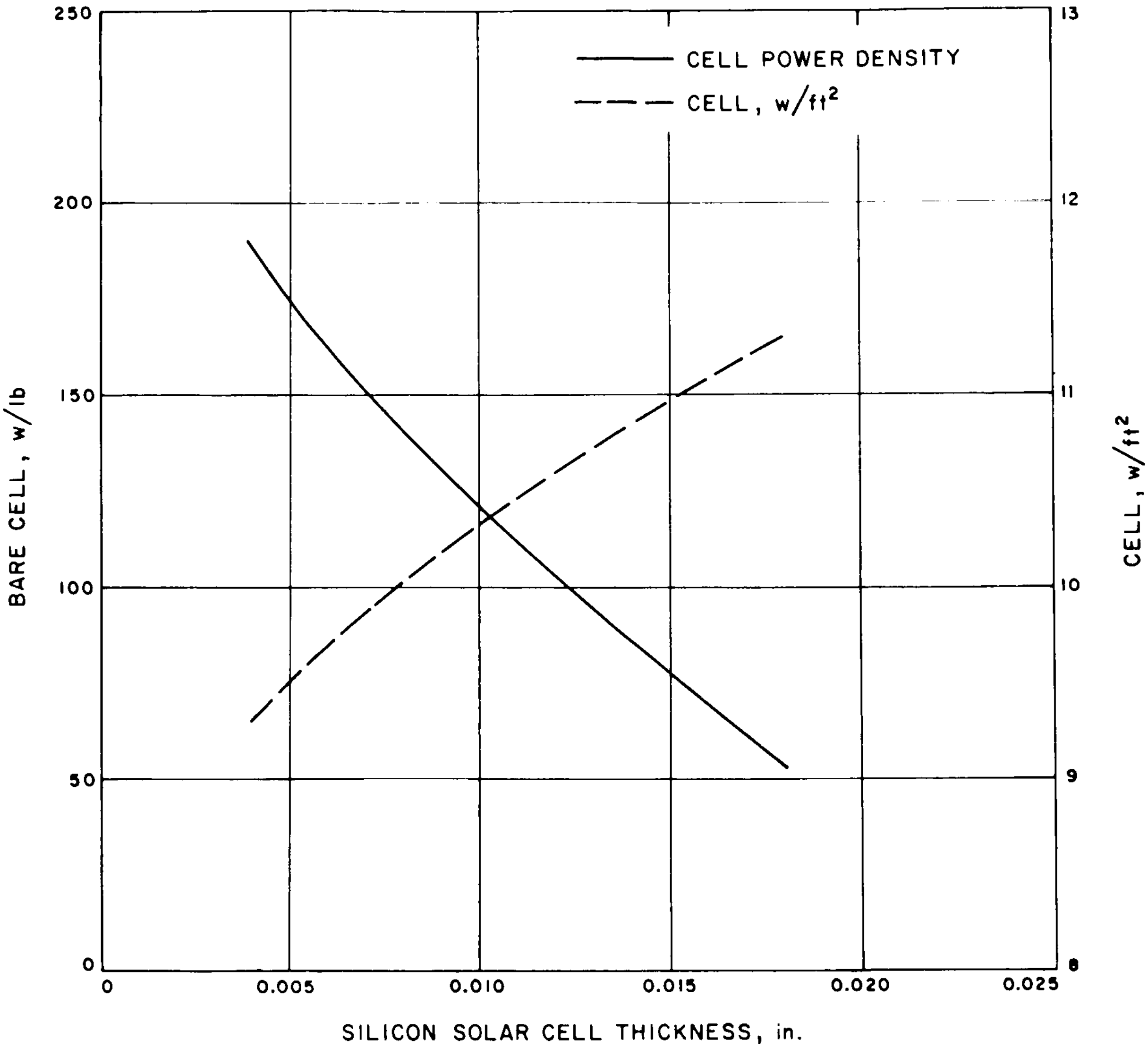

Fig. 2. Silicon cell efficiency and specific power as a function of thickness

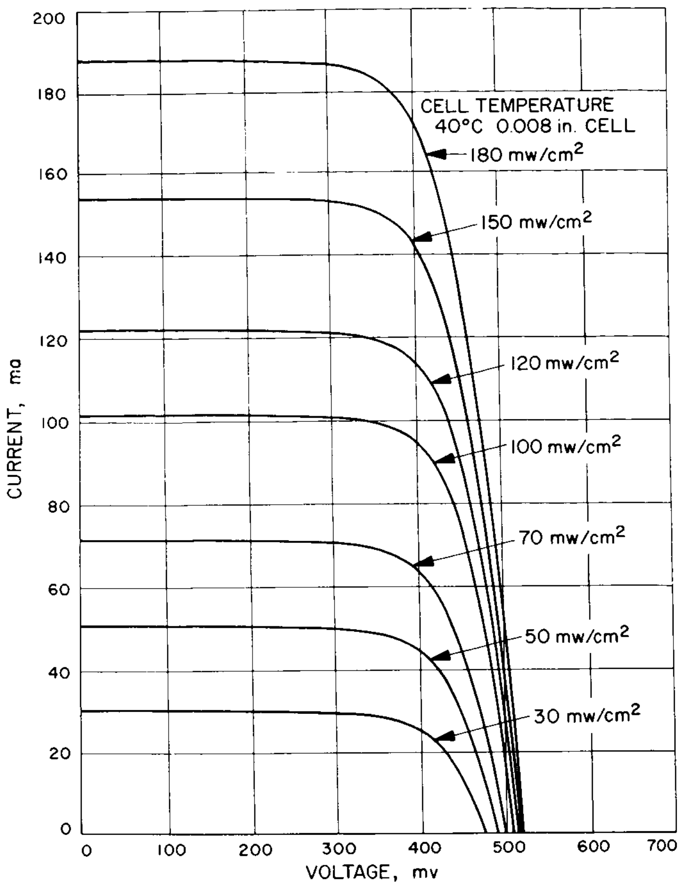

Fig. 3. N/P silicon cell characteristics as a function of incident intensity

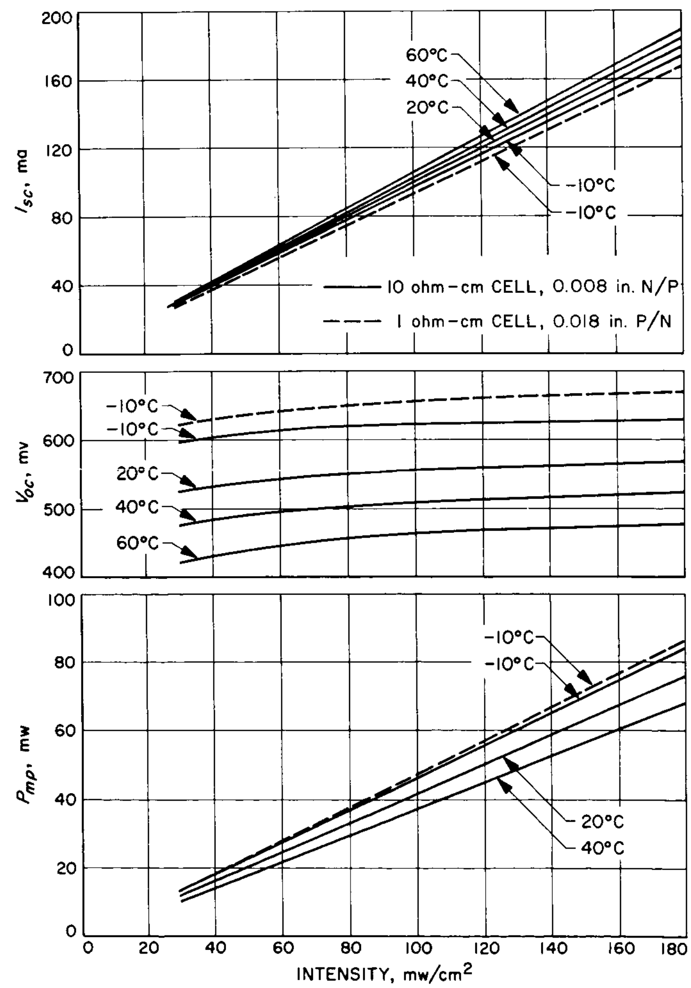

Fig. 4. A comparison of N/P silicon cell characteristics as a function of intensity and cell temperature

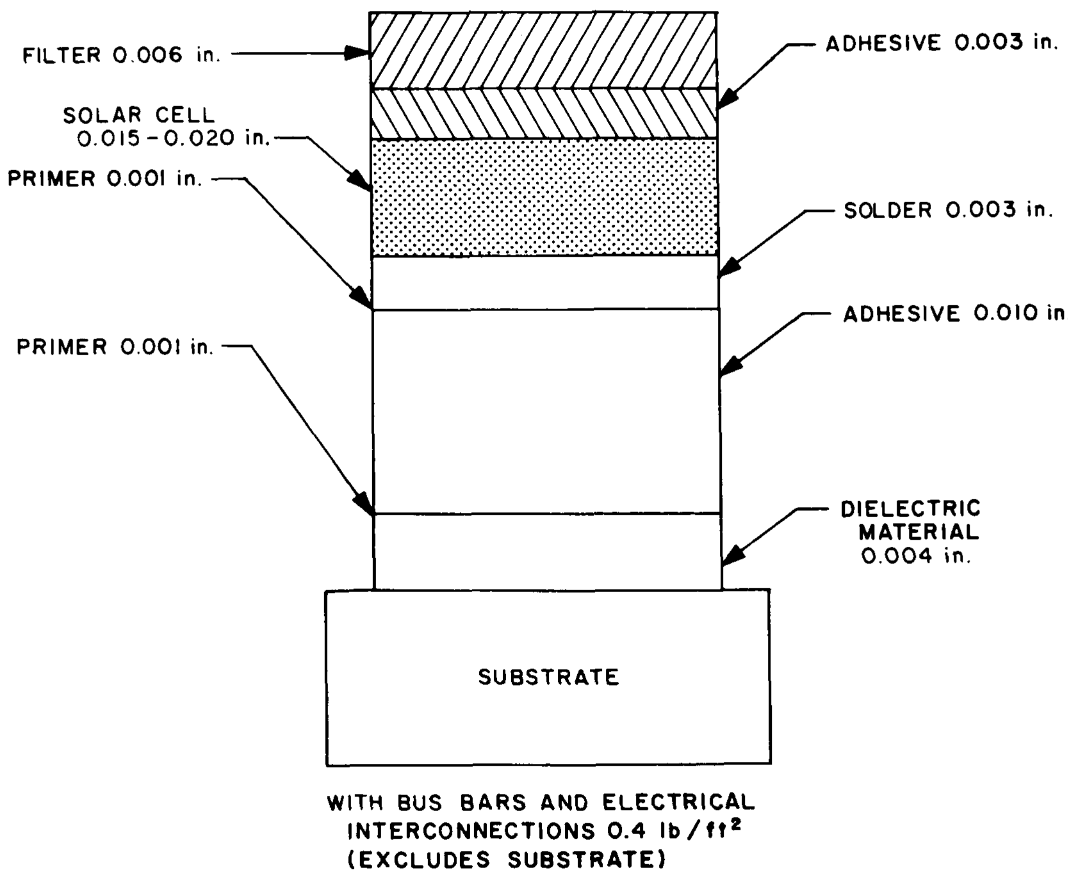

Fig. 5. Typical solar cell stack representing the 1965 solar panel technology

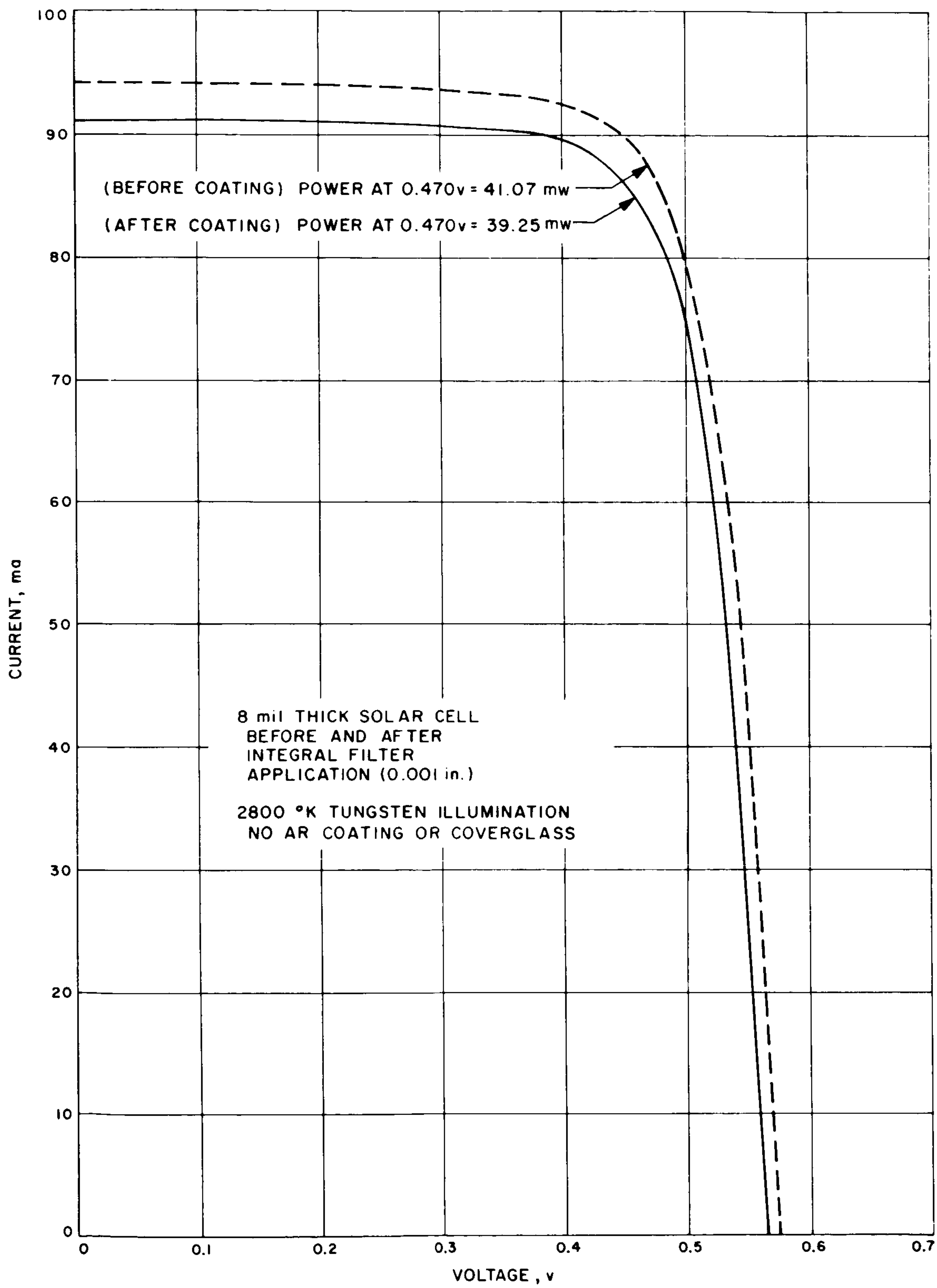

Fig. 6. Solar cell *I-V* characteristic before and after application of integral coating

Table 1. Comparison of solar cell stack weights and power densities

Materials	*Mariner IV*	Developmental 0.008-in.-thick cell	Developmental 0.004-in.-thick cell
Cell	0.206 lb/ft²	0.070 lb/ft²	0.049 lb/ft²
Filter	0.058 lb/ft²	0.033 lb/ft²	0.011 lb/ft² (0.001 in. integral)
Filter adhesive	0.010 lb/ft²	0.010 lb/ft²	NA
Bus bars	0.024 lb/ft²	0.024 lb/ft²	0.024 lb/ft²
Dielectric	0.023 lb/ft²	NA	NA
Intercon-nections	0.025 lb/ft²	0.025 lb/ft²	0.025 lb/ft²
Thermal coatings	0.025 lb/ft²	0.025 lb/ft²	0.025 lb/ft²
Mounting adhesive	0.020 lb/ft²	0.010 lb/ft²	0.010 lb/ft²
Total stack weight	0.391 lb/ft²	0.197 lb/ft²	0.144 lb/ft²
Power density[a]	9.7 w/ft²	10.0 w/ft²	9.3 w/ft²
Specific power[a]	24.8 w/lb	50.8 w/lb	64.6 w/lb

[a]Air mass zero 140 mw/cm² at 55°C.

Future expansion of the photovoltaic energy converter could be realized by the CdS-type solar cell. The CdS thin-film solar cell is a photovoltaic device made from vacuum deposition of semi-conducting CdS onto a conducting or non-conducting substrate. Present pilot line techniques employ a *front wall* technique in which the CdS is deposited on a metal foil, and the front collector grid is attached by lamination of sheets of clear plastic. The present electrical performance of the CdS solar cells is discouraging when directly compared to silicon. The AM0 efficiency of the CdS cell at 55°C yields 5.6 w/ft² or a cell power density of only about 90 w/lb. This is comparable to a bare silicon cell thickness of 0.012 in. The present efficiency range of the CdS cell prohibits its present consideration for usage. However, with a possible cell efficiency increase to 8 to 10% AM0 at 28°C and the possibility of applying flexible CdS solar cells for compact roll-up type applications, it may offer a potential for photovoltaics in the 1970's.

IV. Systems Technology

In considering the usefulness of the higher power density (w/lb) silicon solar cells that are available today, mission criteria, launch environment, structure, and system dynamics reflect on overall solar array potential weight advantages. As shown in Fig. 7, using the *Mariner IV* solar cell stack and plotting the stack weight vs allowable structures and mechanisms weight, the advantages of the thinner cell become apparent. This set of curves is based on the *Mariner IV* cell stack and varies only the cell thickness. Even greater structures and mechanisms allowable weight can be obtained by the use of the 0.003-in.-thick filter glass, or integral coating and the 0.004-in.-thick solar cell. As indicated in the curve at 25 w/lb, the increase in structures and mechanisms allowable weight is 22% between the 0.012-in. and the 0.008-in. thickness silicon cell. This could be a significant factor for consideration pending spacecraft mission constraints. The full impact of weight reduction of the solar array and overall power density (w/lb) is strongly dependent on the spacecraft loads during the boost and cruise phase and the interaction of the dynamics of the attitude control system and the solar array.

The trend in photovoltaic solar arrays has been to establish the state of the art for producing large area, lightweight solar arrays. Emphasis has been placed upon increasing the power-to-weight ratio (w/lb). The folding modular and roll-up systems are essentially two basic solar array configurations which appear most likely to obtain the objectives of high power density and large area deployment.

There are currently several major efforts being carried out by government agencies and industry in the development of large-area, lightweight solar arrays which have power potentials in the kilowatt range. The most notable is the folding panel configuration shown in Fig. 8 which is being developed by the Boeing Co. under the direction of the Jet Propulsion Laboratory. The array criteria have been established around an unmanned electrically propelled spacecraft that has been launched by a *Saturn/Centaur* booster directly into a heliocentric Mars fly-by orbit. The power of such a system would be nearly 46 kw at a sun-probe distance of one astronomical unit. This is achieved through the deployment of 4590 ft² of active solar cell area, at approximately 10 w/ft². A gross deployment area of 5,000 ft² is necessary and includes nonactive structural and mechanical area. The total array weight has been calculated to be 1909 lb for a power-to-weight ratio of approximately 24 w/lb. The array will utilize

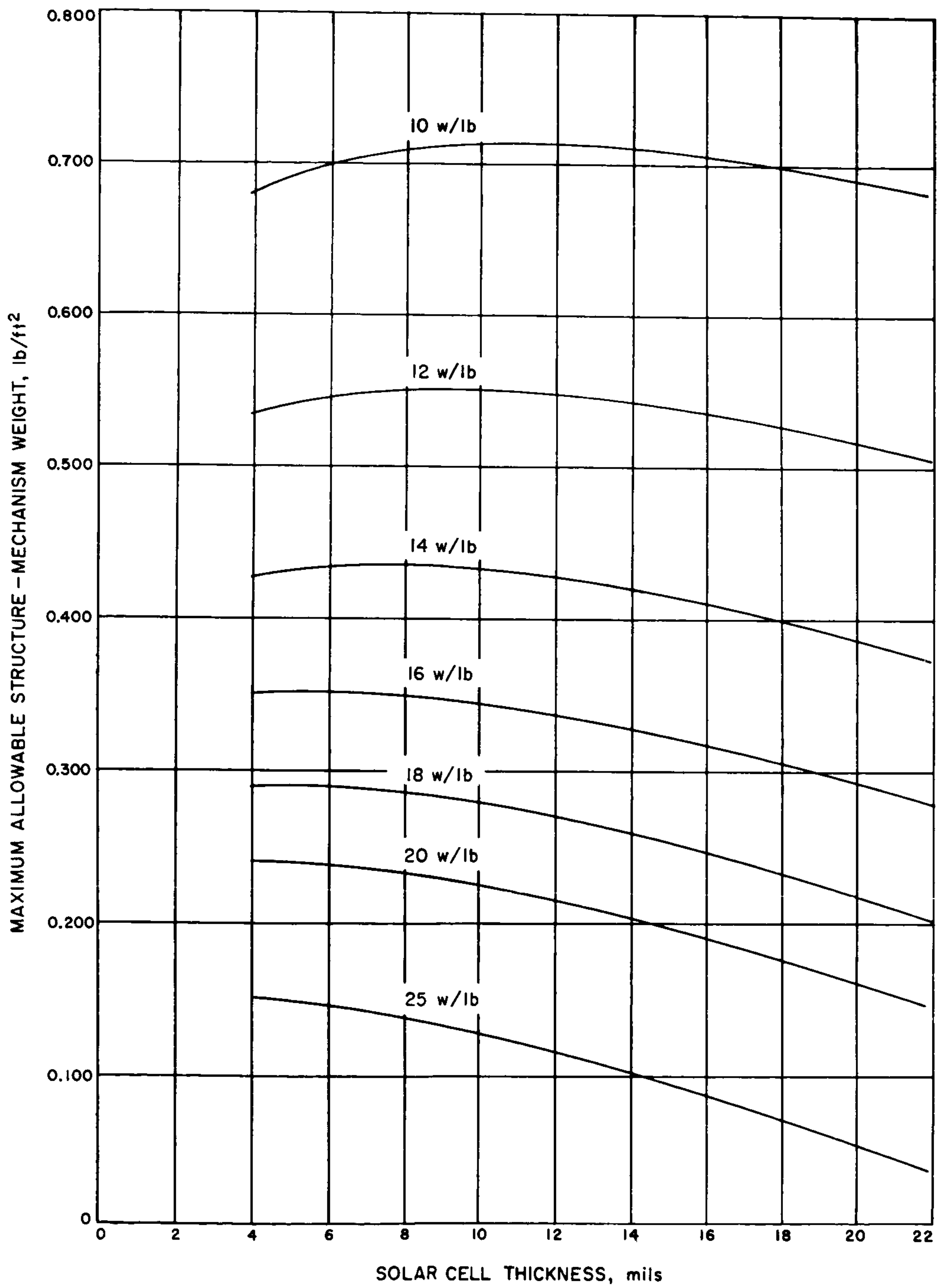

Fig. 7. Allowable structures weight (lb/ft²) at various levels of specific power as a function of cell thickness

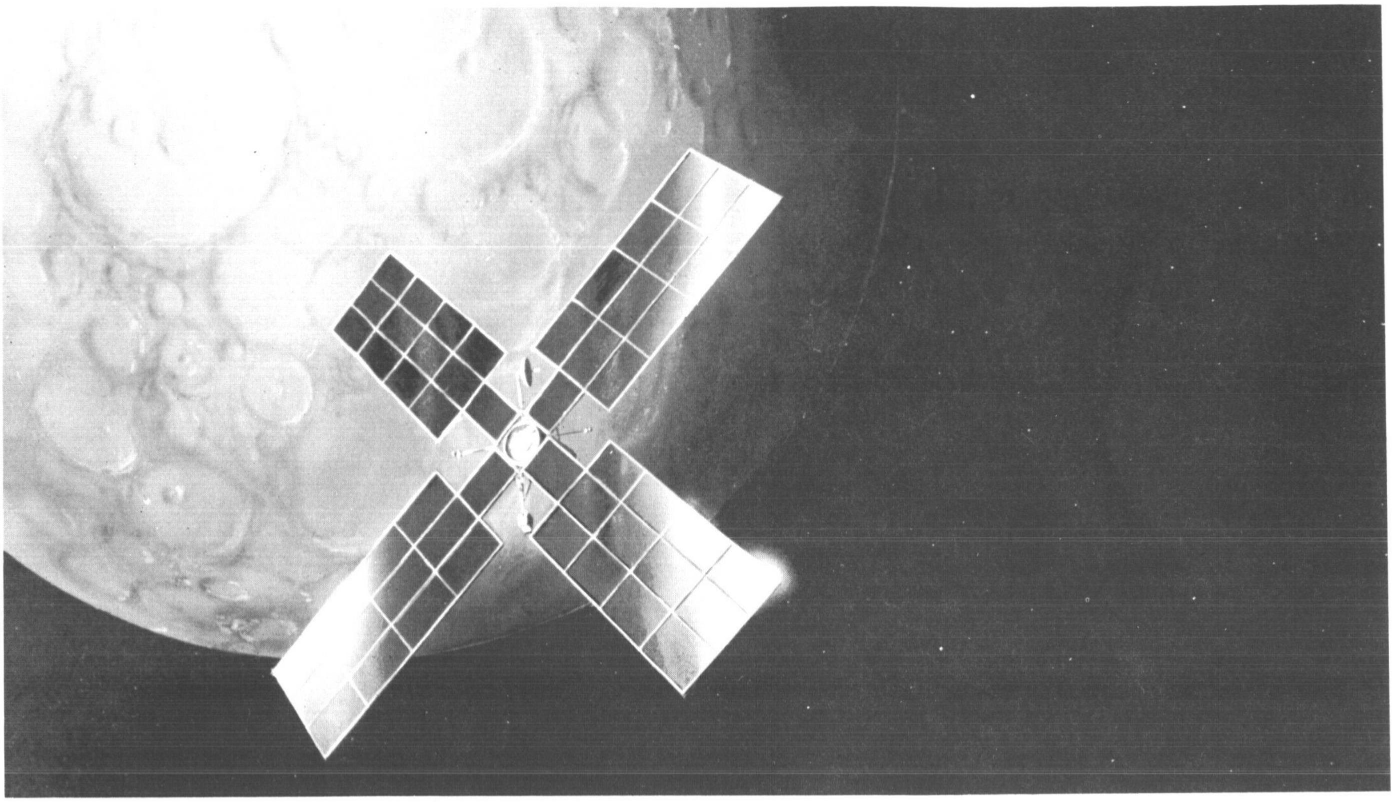

Fig. 8. Conceptual design of solar electric propulsion spacecraft system

0.008-in.-thick solar cells with efficiencies of about 9 to 10% AM0 at 28°C. The solar cell stack in this concept is illustrated in Fig. 9. The structure and deployment devices necessary for obtaining large-area, lightweight solar arrays offer some challenging problems to the designer when the overall array weight is dominated by the mission criteria.

Some of the problems facing the design engineer for the large-area, lightweight array involve the controlling of assembly processes to control accurately adhesive bondlines to minimize weight. Manufacturing techniques for forming beryllium channels up to 13 ft in length with thin gauge material must be accomplished to obtain weight and stiffness requirements of the array design. A major engineering problem is the verification of dynamics of the total array using suitable ground support equipment which imposes a minimum influence to actual array dynamics. The verification of the array dynamic analyses is required because solar array structures of this size have not been built before.

Presently, the development of a 1250 ft^2 element of the 5000 ft^2 array is in progress. To date the first detail design of the array has been completed and tests have been performed to establish design allowables on basic materials. Several problems have been identified by analysis, and solutions to these problems are being undertaken. Beryllium creep-forming techniques are being investigated and to date have been completed with limited success. By analysis, detail design, and limited testing, indications are that problems may exist in dynamic testing and manufacturing techniques which hopefully will be overcome by further development in this effort. To date there have been no significant problems that preclude the realization of multikilowatt, lightweight solar arrays of the folding modular type.

In addition to the large areas achieved in the folding modular design, further advantages may be realized with roll-up array concepts in optimizing the ratio of the deployed active cell area to the stowed volume within the launch shroud. Because of reduced g loads encountered after launch, much lighter weight structural members can be deployed as substrate support to improve the specific power capability of the array. Other advantages of the roll-up concept would be the capability of retracting the array either partially or completely if required;

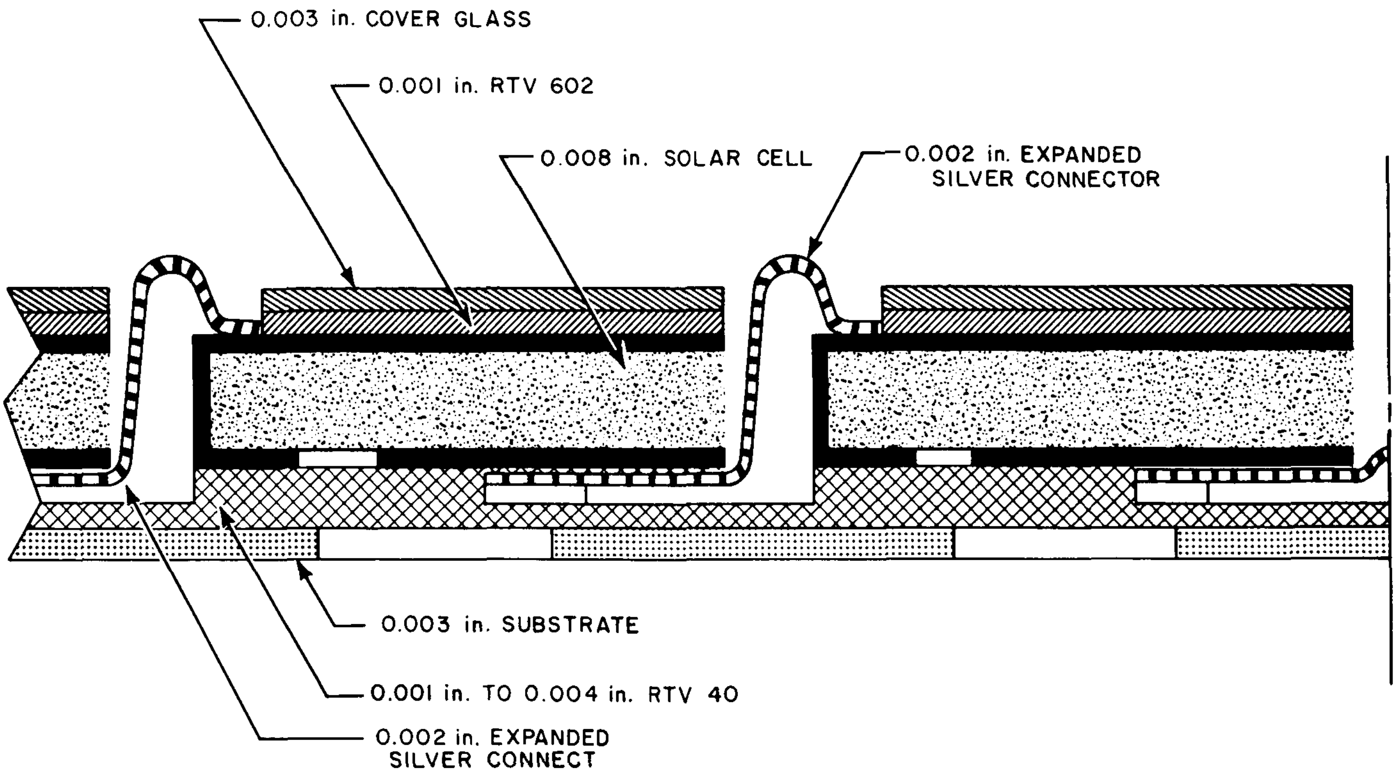

Fig. 9. Advanced solar cell stack concept

e.g., during midcourse maneuver, over periods of high solar activity, or during transition through trapped radiation zones. However, the relative importance of this advantage depends on the details of the mission, boost vehicle, interaction with other systems, reliability, and the numerous tradeoffs that could be implemented in lieu of such a capability.

Several programs are being conducted throughout the aerospace industry to develop the concepts and technology required for designing and fabricating deployable large-area solar cell array structures. Figure 10 illustrates one concept of a roll-up solar array which has been developed by Ryan Aeronautical Company under the direction of the Jet Propulsion Laboratory. The phase I portion of the program included concept evaluation and analysis of deployment methods. The array concept was to be compatible to areas from 150 to 400 ft^2, with 200 ft^2 assumed as a target size. The phase II effort included detail design of a four-element 200-ft^2 deployable array structure designed to a total weight objective of 0.6 lb/ft^2 including 0.3 lb/ft^2 for the cells, filters, modular wiring, and harness. The phase III has been a manufacturing effort of a single deployable 50-ft^2 solar panel assembly with modular substrate sections to demonstrate feasibility of the design concept and deployment system. This deployment concept requires an electric motor geared to a 12-in. diameter wrap drum by a magnesium ring gear. Collapsible 6-mil-gauge titanium beams travel through a beam guide section which is a transition region which passes the beams from a fully expanded mode to a compressed configuration, subsequent to being wrapped around the drum assembly. A flexible 3-mil-thick fiberglass substrate is attached between the beams by connecting tabs. Silicone ½-in. diameter pads are located over the substrate back-surface area to cushion the layers of solar cells while the array is in the stowed position. The completely assembled 50-ft^2 roll-up array excluding solar cells and electrical interconnections weighs 25.1 lb. Assuming 0.3 lb/ft^2 for solar cells, cabling, adhesives, and interconnections, a power-to-weight ratio of 12.5 w/lb is exhibited. With optimization of structural components and incorporating the thinner, lightweight silicon solar cells, an even greater potential or power density may be realized in this particular roll-up array design.

An entirely different deployment concept is shown in Fig. 11 which utilizes a negator spring motor and screw jack mechanism to achieve deployment. Support for the substrate in the deployed configuration is provided by

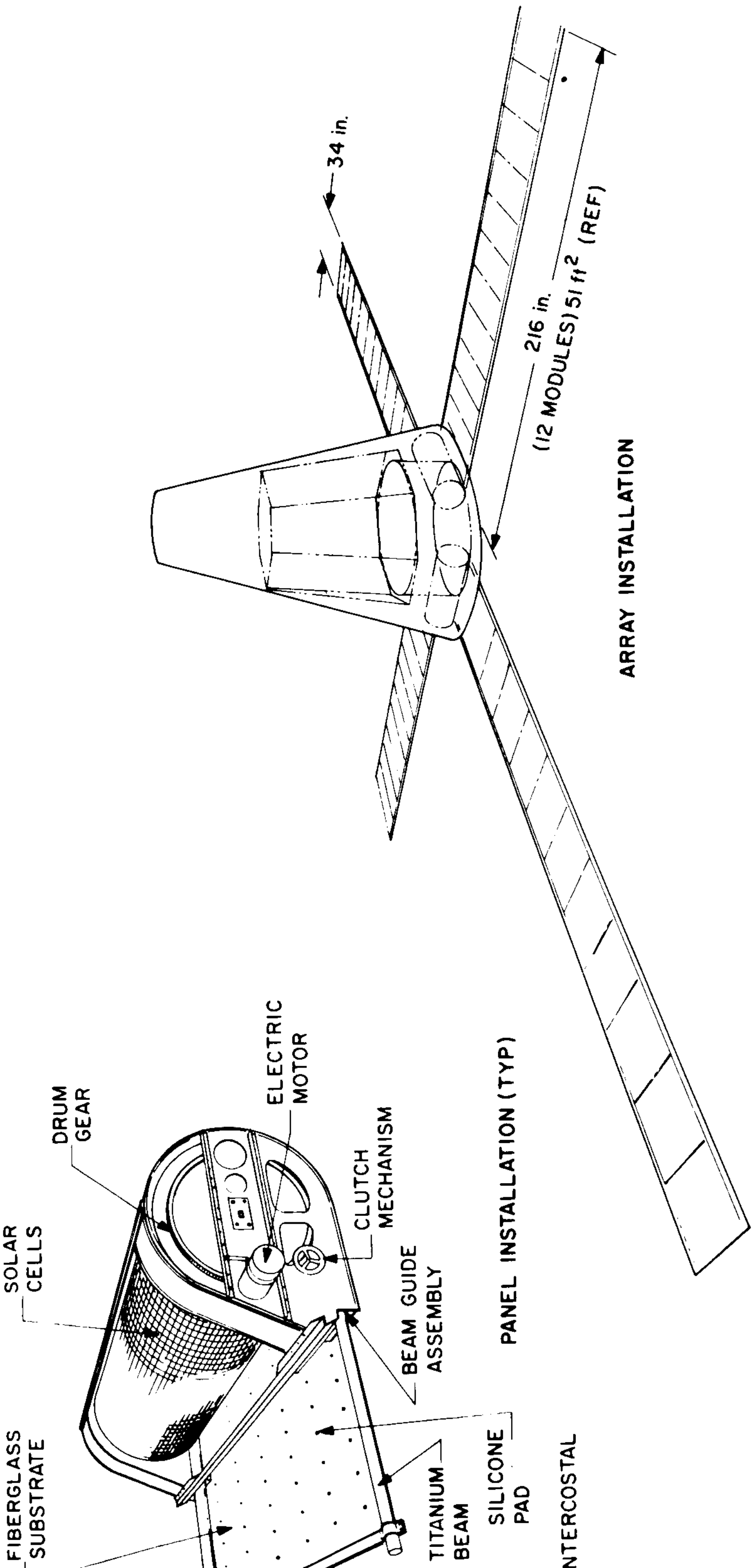

Fig. 10. Deployable solar array utilizing collapsible beams

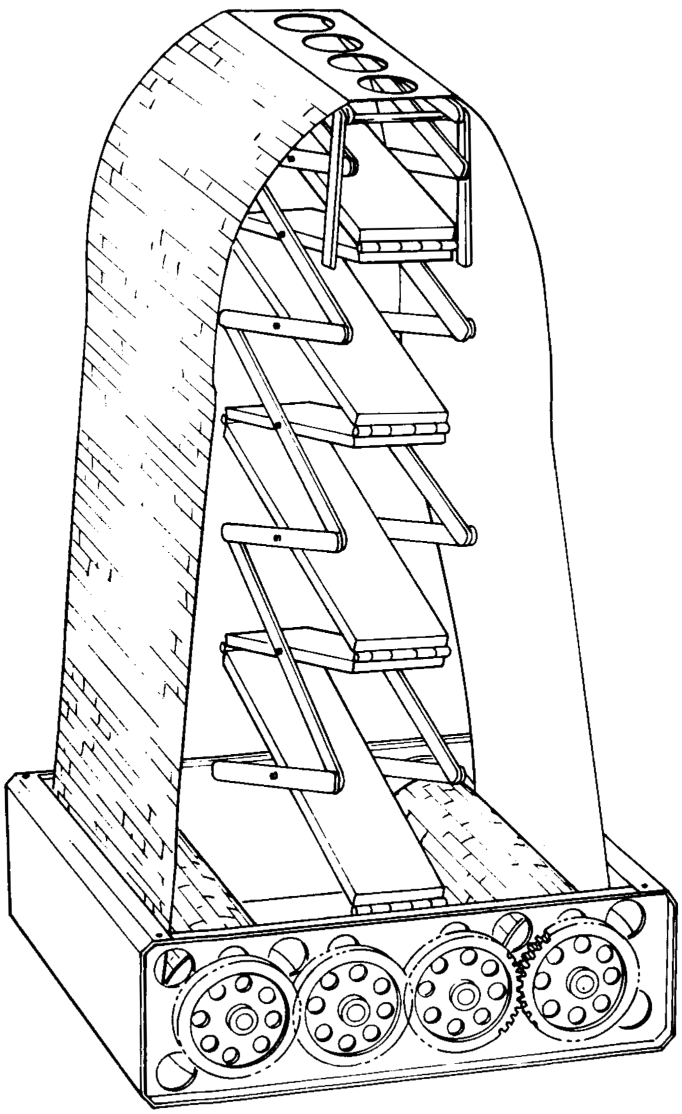

Fig. 11. Roll-up solar array utilizing negator springs as deploying mechanism

the scissor-type linkage. This program is being conducted by Fairchild Hiller under the direction of Goddard Space Flight Center. This concept is especially adaptable to a spinning vehicle where both the front and back surface of a flexible substrate are mounted with solar cells.

A third deployment concept, exhibited by Fig. 12, has been developed by Hughes Aircraft Company under the direction of the Air Force Aero Propulsion Laboratory. This design incorporates a common storage drum for the flexible substrates which deploy diametrically opposite one another. Takeup reels are provided to accept the protective foam cushion as the substrates are deployed. This deployment concept is made possible through the advent of an extendible boom which is stored in a flat form, analogous to a tape, and when released forms a continuous tubular section. A similar concept is a spring tape that is wound at an angle to the longitudinal axis of the extendible tube such that when released from the flat coiled storage position the springs form a conical tube. This technique has been utilized by Lewis Research Center to assemble a matrix of 3 × 3-in. CdS cells into a 16-ft^2 deployable solar array. The array was used as a demonstration model to illustrate interconnection techniques and the applicability of CdS cells to roll-up array configurations.

The events of the past year have clearly demonstrated that roll-up solar arrays are feasible structures. Large-area, lightweight roll-up arrays utilizing state of the art 8-mil silicon solar cells offer attractive power conversion-to-weight ratios for the future.

V. Conclusions

In summary, the silicon solar cell has proven to be a reliable method for obtaining electrical energy from the

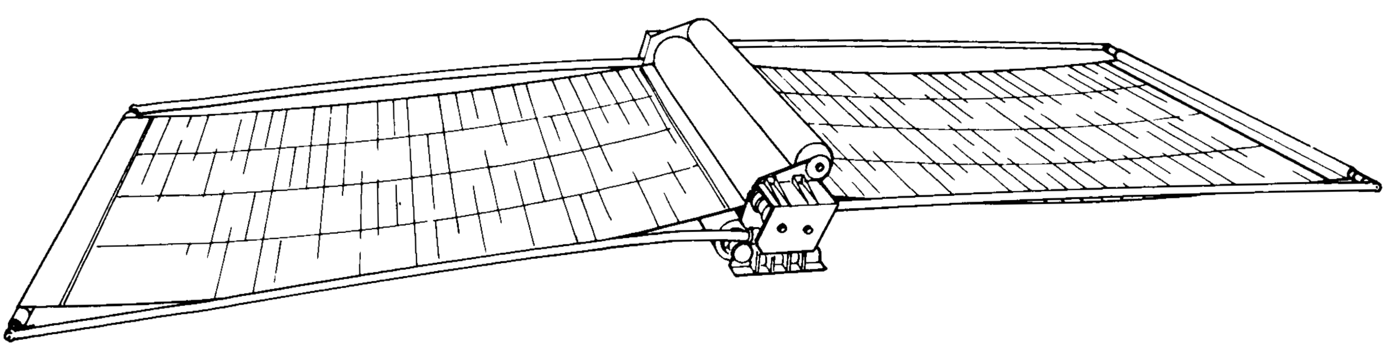

Fig. 12. Roll-up solar array utilizing De Havilland stem tubes as the deployable mechanism

sun for lunar, planetary, and interplanetary spacecraft missions. The potential for the photovoltaic device appears to be expanding to capabilities of high-power, lightweight photovoltaic array systems through the optimization of cell parameters and developments in structures and deployment techniques. The feasibility of folding modular support structures and roll-up solar arrays has been demonstrated to indicate capabilities up to the 50-kw power level with attractive weights and stowage volumes. With present development efforts tailored to these objectives, the realization of multikilowatt solar array technology is expected by 1969.

References

1. Cherry, W., and Zoutendyk, J. A., "The State of the Art in Solar Cell Arrays for Space Electrical Power," AIAA Paper No. 64-738, presented at Third Biennial Aerospace Power Systems Conference, AIAA/SAE/ASME/IAPG/Electron Devices Group IEEE, Philadelphia, Pa., September 1–4, 1964.
2. Wolf, M., and Ralph, E., "Effects of Thickness on Short Circuit Current," Fourth Photovoltaic Specialists Conference Proceedings, PIC SOL 209/5, January 1966.